ASME Journal of Mechanical Design
Online journal at:
https://asmedigitalcollection.asme.org/mechanicaldesign

Analysis of Collaborative Assembly in Multi-User Computer-Aided Design

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Cloud-based multi-user computer-aided design (MUCAD) tools have the potential to revolutionize design team collaboration. Previous research focusing on parametric part modeling suggests that teams collaborating through MUCAD are more efficient at producing a CAD model than individual designers. While these studies are enlightening, there is a significant gap in understanding the impact of MUCAD on assembly modeling, despite assembly's crucial role in the design process. Part and assembly models are both defined by parametric relationships, but assembly models lack hierarchical feature dependency; we propose that by modularizing tasks and executing them in parallel, teams can optimize the assembly process in ways not possible with part modeling. Our study aims to examine and compare CAD assembly performance between individuals and virtual collaborative teams using the same cloud MUCAD platform. Through analyzing team communication, workflow, task allocation, and collaboration challenges of teams comprising 1–4 members, we identify factors that contribute to or hinder the success of multi-user CAD teams. Our results show that teams can complete an assembly in less calendar time than a single user, but single users are more efficient on a per-person basis, due to communication and coordination overheads. Notably, pairs exhibit an assembly bonus effect. These findings provide initial insights into the realm of collaborative CAD assembly work, highlighting the potential of MUCAD to enhance the capabilities of modern product design teams. [DOI: 10.1115/1.4063759]

Keywords: collaborative design, computer-aided design, design theory, design methodology

1 Introduction

Computer-aided design (CAD) software has become ubiquitous in the product design and development field. While technological advancements have revolutionized all manner of design tools, including CAD, traditional single-user CAD software remains prevalent [1], limiting the collaboration capabilities and needs of today's designers. Traditional CAD relies on individual-focused check-in/check-out style processes of product data management systems or manual data management systems (e.g., Dropbox) for sharing and managing virtual design artifacts [2]. Such long-standing workflows pose challenges for geographically-distributed teams, designers working across company boundaries, or design teams aiming to solve early design conflicts [3].

Recent years have seen a transformative shift in CAD technology, marked by the emergence of cloud-based synchronous multi-user computer-aided design (MUCAD)—or *collaborative CAD*—that provides a more robust solution for CAD collaboration. Collaborative CAD platforms, like ONSHAPE[2] and AUTODESK FUSION360,[3] enable multiple designers to edit and review a CAD model interactively, concurrently, and synchronously [4]. These CAD tools not only facilitate distributed and hybrid collaboration modalities, but also introduce affordances like centralized data management, streamlined model retrieval, and new ways for designers to interact with CAD artifacts in the same multi-user working environment [5,6]. As a result, collaborative CAD has the potential to fundamentally reshape the way that design teams construct CAD models, as well as upend our understanding of the CAD design process.

There is a growing body of research that recognizes the importance of understanding team collaboration using MUCAD, which has explored: part modeling [7]; identifying the benefits of collaborative CAD [8]; and comparing single-user CAD to MUCAD modeling [9]. The focus of previous work has been predominantly on parametric part modeling, where a team of designers collaboratively models a single part in collaborative CAD. Although part models are vital to the CAD process, it is equally crucial to consider assembly models, which are models comprised of multiple parts/components. Assembly models are important design artifacts to study because the majority of products—both simple and complex—are composed of more than one part. Despite the significant impact that successful assembly can have on the product design process [10,11], minimal research has investigated how a MUCAD environment might affect a team collaborating on assembly work. Therefore, our work aims to gain a deeper understanding of how CAD assemblies are made, using the modern tools available

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Contributed by Design Automation Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received May 9, 2023; final manuscript received September 28, 2023; published online November 7, 2023. Assoc. Editor: Nicolás F. Soria Zurita.

to designers today. We seek evidence to support or refute the notion that collaborative CAD can potentially change the way design teams optimize the assembly process.

Specifically, our paper aims to address the following four research questions:

- **RQ1:** Are multi-user teams (of up to four members) more productive at CAD assembly compared to one person working solo in the same collaborative CAD platform?
- **RQ2:** Does the complexity of the assembly affect the individual's or team's productivity?
- **RQ3:** How do the best-performing teams communicate compared with the worst-performing teams?
- **RQ4:** What are common challenges in collaborative CAD assembly? How can CAD systems be improved to assist collaborative assembly?

We present the results of an experiment which studied how groups of 1–4 designers collaborate during synchronous CAD assembly to answer our research questions. Our findings are a first step toward guidance for CAD managers and designers in deciding how to staff their CAD assembly tasks, how to maximize productivity, and how to distinguish high-performing CAD teams from low-performing CAD teams. Our work also considers qualitative participant input to provide additional insights for the advancement of collaborative CAD platforms.

2 Background and Related Work

2.1 Computer-Aided Design Assembly. "Assembly" broadly refers to "the addition or joining of parts to form the completed product" [12]. In the context of CAD, an assembly is a model composed of components and/or subassemblies connected by mates and assembly relationships [13,14]. This differs from part modeling, which is the modeling of a product element that is to be manufactured in one single piece [14]. Assembly relationships consist of constraints, mates, or links that describe the relative position of each component in an assembly [14]. Mates can define the position and motion of components in relation to each other. For example, a mating condition can be added to align holes concentrically, or to make two faces parallel. In addition to mating conditions, components can also be positioned within the assembly by way of absolute coordinate placement methods. The final position of each component based on these relationships is calculated using a geometry constraint engine built into the CAD system.

Mating conditions can vary depending on the CAD system being used. In the collaborative CAD system, ONSHAPE, the movement (degrees-of-freedom) between two instances is embedded within the mate, thus only one mate can be added between any two entities. For example, when modeling a simple fan assembly, the traditional CAD package, SOLIDWORKS, requires two mates between the pin and fan: (i) a coincident mate to limit translation in the Z-direction and (ii) a concentric mate to define the rotational relationship between the two parts (Fig. 1). In ONSHAPE, only one revolute mate is required, which constrains all motion except for rotational movement about the Z-axis.

Past research regarding CAD assembly has focused on understanding and optimizing assembly sequence planning [15,16], evaluating assembly similarities [17], assembly model retrieval [18], and automating the assembly process [19,20]. However, few studies explore how to optimize CAD assembly when using collaborative CAD.

2.2 Assembly Complexity. Researchers in various fields have extensively explored the concept of complexity, resulting in a wide range of definitions and methods by which to measure it [21]. Generally speaking, a "complex assembly" describes a difficult and demanding assembly. In fact, existing complexity models are theoretical, and there is no universally accepted method for measuring complexity [22]. As a result, many researchers have attempted to generate their own techniques for defining complexity in the context of assembly. Rodriguez-Toro et al. suggested that there are two elements of complexity: component and assembly, where component complexity is related to the geometry of components and the assembly complexity is related to the product's architecture and the number of operations (mating relationships) required to create the assembly [23]. Alkan et al. defined the complexity of a product as the degree to which both the complexity of the assembly components and their mating relationships cause difficulties during the handling or fitting processes in assembly [24]. Falck and Rosenqvist interviewed 64 engineers involved in design and manufacturing to study how industry professionals understand the concept of assembly complexity [25]. They found that 92% of

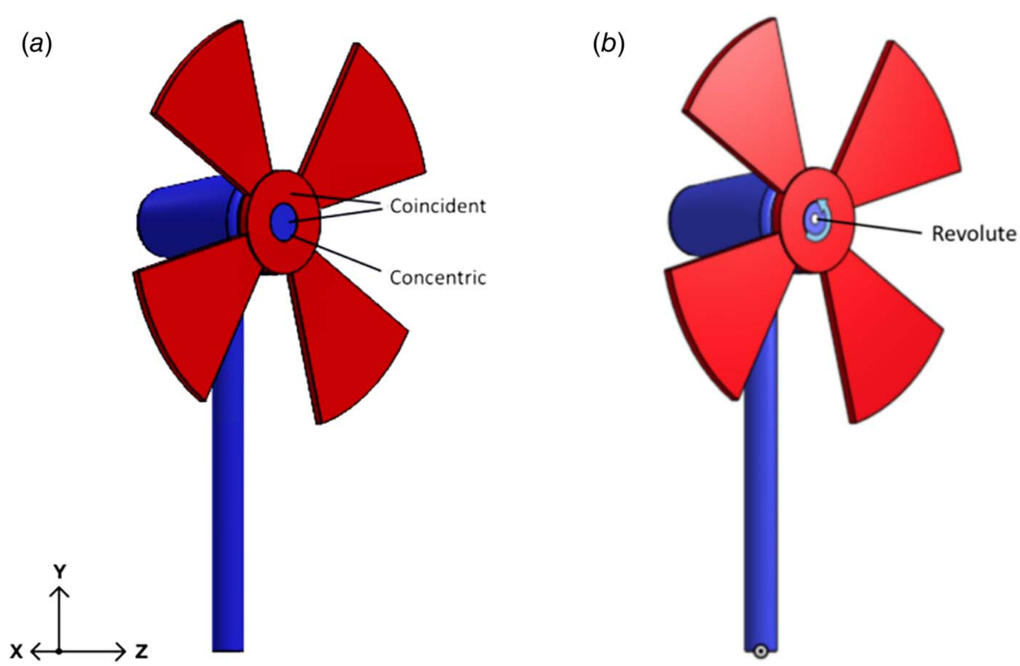


Fig. 1 Fan assembly mates in (*a*) SOLIDWORKS and (*b*) ONSHAPE

respondents believe there is a direct relationship between assembly complexity and assembly time [25]. This suggests that complex assemblies take longer to complete than simple assemblies. Evidently, there are many different, yet valid, definitions and understandings of assembly complexity.

Other researchers have recognized this lack of agreed-upon methodology to measure an assembly's complexity [26–28]. Henning et al. sought to address this issue by benchmarking common complexity measures to assess their validity [28]. They tested six different complexity measures commonly used in the mechanical design community on different "commonly held beliefs" about complex systems, which included: (1) complexity increases with size (i.e., number of components) and (2) complexity increases with interconnectedness (i.e., number of connections between components). Hennig et al. found that not all complexity measures responded similarly to changes in size or interconnectedness; in fact, only Halstead's derived volume measure (HVM) was sensitive to both increases in size and interconnectedness [28].

In this study, we aim to observe teams collaborating synchronously to assemble models of low, medium, and high complexities. We investigate if and how complexity affects the assembly's completion time. As seen in the literature, there are no universally accepted metrics for complexity, but by providing this literature review, we can better evaluate the numerous existing measures, and substantiate the complexity measures we select for evaluating the CAD assembly models in our study. Drawing insights from the body of literature on assembly complexity, it is apparent that researchers commonly concur that both size (number of components) and interconnectedness (number of mating relationships) are key contributors to an assembly's complexity. As such, we use these metrics in our methodology, further elaborated in Sec. 3.2.

2.3 Modularity. Modularity is an organizational tactic in which complex systems can be decomposed into simpler subsystems (or modules), to be managed independently [29]. Modularity (or modularization) can improve the way in which assemblies are made [30,31]. For example, a modular assembly can be divided into smaller, more manageable "subassemblies," where each subassembly contains a set of components that are highly dependent on each other, but minimally dependent on components outside of their subassembly [32]. Previous work regarding modularity uses network structures to represent systems and subsystems, as a visual method to convey the connectivity or dependencies between modules [33–35].

To understand the dependencies between components and/or subassemblies, we apply a concept frequently used in software development. Feature dependency is a terminology that describes code containing program elements that depend on other elements to function [36]. A similar idea can be applied to CAD modeling, where certain CAD parts' features depend on other features (e.g., a sketch needs to be extruded before a fillet can be added). Features in CAD modeling follow a "parent/child" relationship structure, such that each feature is connected hierarchically [37]. Due to this dependency, modifications to a parent feature will propagate to related child features [38]. Hartman explains that CAD designers must initially strategize a modeling plan to increase efficiency and minimize errors, as improper feature sequencing can lead to longer modeling times, impossible geometries, and feelings of confusion [39]. Hence, a multi-user CAD team modeling a single part simultaneously must have heightened awareness of each other's work and also of how one member's modifications to parent features will propagate to affect another member's child features.

In CAD assembly, however, mating relationships (i.e., assembly features) do not follow a hierarchical structure. Therefore, assembly features can be added in parallel with other contributors, and team members do not have to wait for each other to finish. We define this type of work arrangement as parallel execution. In computing, parallel execution is when numerous calculations or processes are executed simultaneously, and results are combined at the end, when the program is finished running [40]. We apply this concept to CAD assemblies where subassemblies can be completed in parallel with other subassemblies, resulting in a finished CAD model. To understand how a team of designers would tackle such an assembly task, we use fully synchronous collaborative CAD software. We expect that successful multi-user CAD teams will modularize assemblies and display a parallel execution workflow.

2.4 MUCAD Collaboration. Since its development in 1963, CAD systems have primarily focused on the interactive process between the computer and a single user [4]. However, recent innovations in cloud technology have allowed the CAD industry to develop fully-synchronous MUCAD software [41]. This technology is comparable to "Google Docs," as collaborative CAD enables multiple users to simultaneously create, manipulate, and contribute to the same CAD file, as well as save changes in real-time [42]. Collaborative CAD has numerous potential benefits when compared to traditional single-user CAD: enhanced team communication; improved feasibility for collaboration in geographically-dispersed teams; increased parallelism between, awareness of, and care for other team members; and increased learning opportunities [43–48].

Researchers have previously collaborated CAD's effects on the design process. Eves et al. conducted a study to assess the modeling capabilities of four multi-user teams and four single-user teams when tasked with modeling a hand drill. They concluded that collaborative CAD increases communication between team members and heightens awareness of other team members' work [49]. Hepworth et al. showed that having multiple users contribute to a CAD file greatly reduces the modeling time required [50]. However, they also found that at a certain point, having multiple users actually increases the amount of time spent modeling [50]. This trade-off suggests that there is an optimal number of simultaneous contributors in collaborative CAD, and more contributors do not always lead to better outcomes. Stone et al. investigated methods to determine the optimal team size for designers modeling a single part simultaneously. In this study, teams of 1–4 designers worked simultaneously to model parts of varying complexity (as measured by the number of features required to create the part). They found that, on average, the time required to model a single part decreases as the number of contributors increases, with no significant changes to the reduction of modeling time at around four contributors [7]. Stone et al. further studied the CAD modeling efficiency of individuals and teams and found that efficient teams were more adept at developing shared mental models—highlighting shared mental models as a critical component of effective CAD collaboration [51]. Shared mental models refer to the overlap or convergence among members' mental representations of their tasks, goals, and responsibilities [52].

While there has been considerable research in collaborative CAD part modeling, comparatively fewer studies have focused on CAD assembly in a fully-synchronous collaborative environment. We believe that parallel execution, modularity, and feature dependency will play key roles in the way that multi-user teams work and allocate tasks, differing from the results of previous studies that focus entirely on part modeling.

3 Methodology

The aim of this study is to analyze and compare the performance of individuals and collaborative teams during CAD assembly. The experiment was designed such that all participants, whether working individually or collaboratively, use the same collaborative CAD software.

We selected ONSHAPE as the CAD platform for two main reasons. First, ONSHAPE is a fully-synchronous, cloud-based, multi-user parametric CAD platform. With ONSHAPE, our study participants can engage in real-time online collaboration. Moreover, the platform's cloud-native architecture eliminates many pervasive pain points

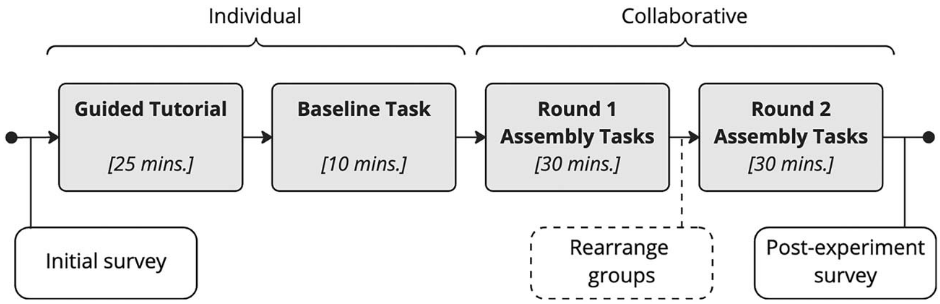


Fig. 2 Stages of synchronous CAD experiment

with prevalent CAD systems [1], such as cumbersome software downloads, software crashes, or the purchase and management of CAD licenses [53]. The second key reason for using ONSHAPE is its capability to offer researchers access to backend data referred to as "audit trails," which capture precise, time-series CAD logs of each action a user makes within the platform, providing a rich and unique dataset. Using these automatically-generated audit trails, we have a streamlined way of recording observational design data in a non-intrusive and highly precise manner, within a specified timeframe. Similar studies on collaborative CAD have leveraged ONSHAPE's audit trails to explore designer emotions [54] and paired CAD modeling [55].

Our experiment was conducted entirely remotely, driven by the increased adoption of collaborative technologies, such as cloud platforms and multi-tenant software [56], that has only been accelerated by the COVID-19 pandemic, forcing designers to work and collaborate remotely [57]. We contend that the migration of design and CAD work to online platforms motivates the need for designers to acquire proficiency and comfort with emerging collaborative CAD tools. Thus, our study aims to explore how these collaborative CAD tools can be leveraged to effectively facilitate CAD assembly in a fully remote environment.

3.1 Experiment Overview. We conducted a synchronous CAD experiment whereby 20 participants were tasked with assembling models of varying complexity in teams of one, two, three, or four members. We assigned teams such that there were two teams for each team size, totaling eight teams (i.e., two single users, two pairs, two teams of three, and two teams of four). Participants were compensated \$15 h, for a total of 2 h. Data were collected in three stages: (1) initial survey to recruit and screen participants, (2) synchronous experiment with CAD assembly tasks, and (3) post-experiment survey.

The synchronous CAD experiment can be broken down into four phases: (1) guided tutorial, (2) baseline assembly task, (3) Round 1 collaborative assembly tasks, and (4) Round 2 collaborative assembly tasks. These stages are summarized in Fig. 2.

The synchronous experiment was held through the online conferencing software, ZOOM.[4] To begin the study session, we required our 20 participants to join a Zoom call under a prearranged, unique alias (i.e., Participant 1, Participant 2, etc.) with their cameras switched off. Once all participants were present, we ran a 25-minute guided training session on the CAD software, ONSHAPE, to demonstrate the user interface (UI), collaboration features, and how to create mates. Following the demonstration, participants were given an individual baseline task of assembling a basic model in order to become familiarized with the study format and for the researchers to calibrate for varying skill levels.

Following the completion of the baseline task, the 20 participants were divided into eight randomly-assigned teams of one to four members to begin the Round 1 collaborative assembly tasks. Each of the eight teams was moved into a separate Zoom breakout room and was allowed to communicate via Zoom audio, messaging, and screen-share only—no video. Participants could also interact through the CAD platform, using the built-in comment feature and "Follow Mode," which allows users to view another collaborator's screen in real-time. Once the teams had joined their breakout rooms, the teams were given 30 min to assemble three different models of varying complexity. The researchers recorded each team's Zoom breakout room session for audio communication data.

After 30 min had elapsed, the participants rejoined the main Zoom session and were randomly reassigned to teams of 1–4 members (again with two teams for each team size, totaling eight teams), to begin the Round 2 collaborative assembly tasks. It should be noted that careful attention was given to the reassignment process to prevent any participant from being grouped with the same team member they had in Round 1. This step was taken to ensure that prior familiarity with team members would not influence our findings. After reconfiguring the teams, teams were then similarly moved into separate Zoom breakout rooms and given 30 min to assemble another set of three different models of varying complexity.

We chose not to employ counterbalancing in our study due to our objective of randomizing teams for each round. Our intention was to mitigate potential influences of team dynamics (such as increased familiarity among members, or imbalanced CAD skill levels) on team productivity. Counterbalancing the assembly sets would have necessitated a fixed sequence, which could potentially have introduced confounding effects.

Immediately following the Round 2 collaborative assembly tasks, participants were free to leave the Zoom session. However, to receive full compensation, participants were required to complete a post-experiment survey to gather qualitative data and feedback. These data were used to analyze the successes and challenges of each team.

3.2 Computer-Aided Design Assembly Tasks. Each round, teams were tasked with adding appropriate mates to pre-modeled CAD parts, and were given 30 min to complete as much of the assemblies as possible. Thus, the terminating condition for the assembly task was the time limit or the successful completion of the assembly.

Team members were allowed to allocate tasks in the manner of their choosing, under the condition that they begin with the least complex model and finish with the most complex model. This being said, only two out of eight teams were able to complete all assemblies in Round 1, and no teams were able to complete all assemblies in Round 2.

For all assembly tasks (including the baseline task), participants were provided with the pre-modeled part files and a task guide containing snapshots of the fully-assembled model from multiple views, as well as a short video of each assembly in motion, when properly assembled. The purpose behind providing pre-modeled parts is to ensure that the parts are consistent across all teams, such that CAD teams are only evaluated on their assembly mating skills rather than their sketching or modeling skills. This

[4]https://zoom.us/

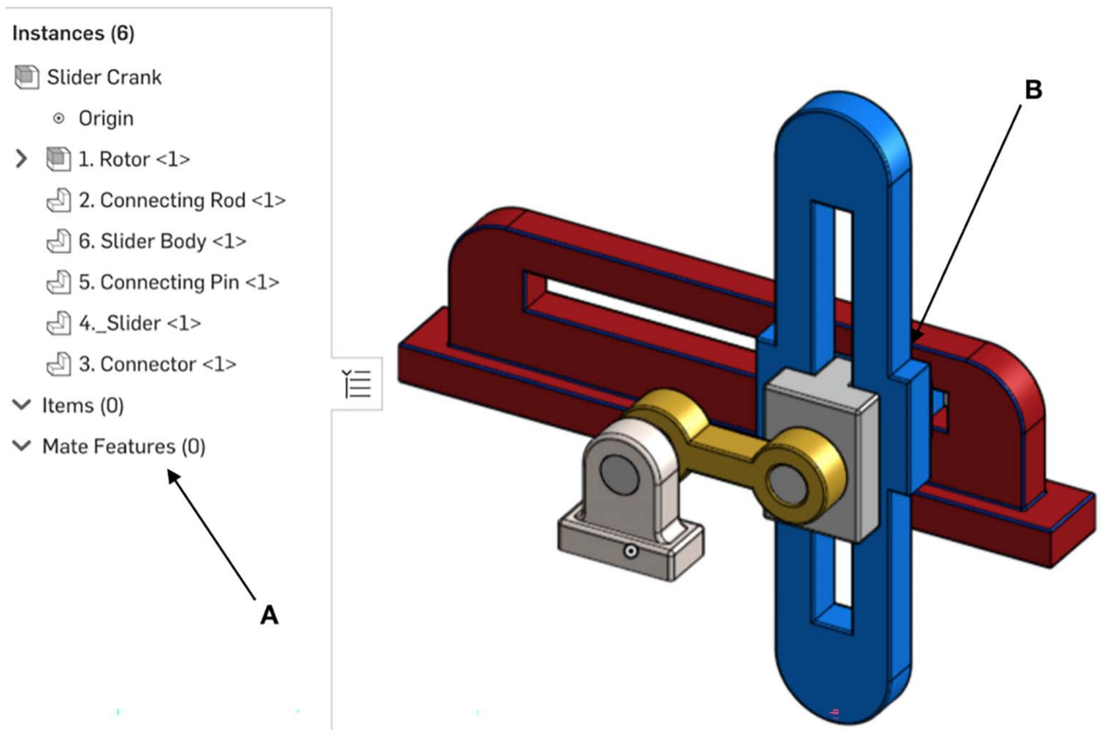


Fig. 3 Assembly model opened in the CAD software which has an (*a*) empty feature tree and (*b*) correctly positioned parts

experiment only involved adding mates, excluding other assembly activities (e.g., importing files). The CAD parts were provided in a single assembly file, so when opened in the software, parts were already in the correct positions. Figure 3 shows how the CAD file would look once opened in the software. While there are no existing mates (Fig. 3(*a*)), parts are positioned correctly, relative to one another (Fig. 3(*b*)).

Each set of assemblies consisted of low, medium, and high complexity models. In this study, complexity is measured by three criteria: (1) the number of parts in the assembly, (2) the average number of mates per part, and (3) the HVM complexity [27,28]. HVM complexity is a suitable measure to quantify complexity in our context, because it is sensitive to increases in both size (i.e., number of components in the assembly) and interconnectedness (i.e., number of mates per component in the assembly) [28]. HVM complexity considers: the number of components (N), the number of interfaces (E), the number of unique components (N_u), and the number of unique interfaces (E_u). HVM complexity is calculated using the following equation (Eq. (1)). Table 1 summarizes the complexity criteria.

$$\mathrm{HVM} = (N + E) * \log (N_u + E_u) \tag{1}$$

Here we will use the Round 1 low complexity assembly (*Quick Return*) for an example calculation of HVM complexity. The number of components (N) = 5; the number of interfaces (in this case, mates) (E) = 6; the number of unique components (N_u) = 5; and the number of unique interfaces (E_u) = 6. Thus, HVM = 11.

Table 1 Measures of assembly complexity

Complexity	Number of parts	Average mates per part	HVM
Low	2–7	1–1.2	≤18
Medium	8–13	1.2–1.5	18–35
High	≥14	≥1.5	≥35

The Round 1 assemblies in order of least to most complex were: *Quick Return*, *Schmidt Coupling*, and *Screw Jack*, shown in the left column of Fig. 4. For Round 2, participants were randomly reassigned to groups of 1–4 members and tasked with completing a different set of three assemblies. The second round assemblies in increasing complexity were: *Cardan Joint*, *Manual Clamp*, and *Hydraulic Scissor Lift*, shown in the right column of Fig. 4. It should be noted that none of the teams had enough time to begin working on the *Hydraulic Scissor Lift*; thus, this model is eliminated from further discussion.

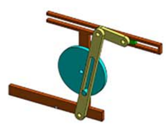
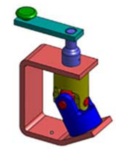
3.3 Baseline Task and Score Adjustment. In our study design, we incorporated an initial baseline CAD task in which each participant was required to independently complete a baseline task of a basic assembly of six pre-modeled parts, immediately following the guided training session.

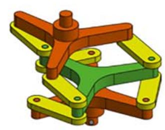
The baseline tasks served two specific purposes. The first reason was to verify the participants' proficiency in parametric CAD skills, ensuring their capability to effectively engage in the experiment. Those unable to successfully accomplish the baseline task (where success is defined as the complete assembly of the model with accurate mates) were requested to withdraw from the study, and their data were not included in our analysis. Only one individual was unable to complete the task.

The second purpose of the baseline task was to provide a way to account for the variation in CAD skill levels across the participants. Past work by Stone et al. and Phadnis et al. has employed a similar method to normalize the modeling speed of a single part for each of their participants [7,58]. The purpose of this task is to generate a time correction factor for each participant to normalize participant modeling skills. The equation for this correction factor is shown in Eq. (2), where R_c is the correction factor, t_{avg} is the average assembly time across all participants, and t_{user} is the individual user's completion time.

$$R_c = \frac{t_{avg}}{t_{user}} \tag{2}$$

	Round	
Complexity	1	2

Low	**Quick Return**
	
	# parts = 5
	# mates = 6
	HVM = 11
		Cardan Joint
		
		# parts = 7
		# mates = 8
		HVM = 16

Medium	**Schmidt Coupling**
	
	# parts = 9
	# mates = 13
	HVM = 20
		Manual Clamp
		
		# parts = 12
		# mates = 16
		HVM = 33

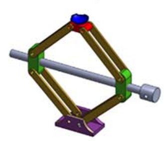
High	**Screw Jack**
	
	# parts = 14
	# mates = 22
	HVM = 37
		Hydraulic Scissor Lift
		
		# parts = 16
		# mates = 25
		HVM = 49

Fig. 4 CAD assembly modeled by participants in the experimental study

It has been argued that the performance of teams whose members are highly interdependent depends most on the team's weakest link in the relevant skill [59–61]. In this study, R_c is used to measure individual skill, so we apply the lowest R_c of the team to the team's overall assembly time in order to normalize the assembly completion times. This assumption was made based on previous observations of collaborative CAD teams, which require high levels of interdependence [7]; teammates must agree on how the assembly moves, which mates to use, and who will mate which components.

3.4 Participants. To recruit participants, an announcement was posted in the University of Toronto Engineering Facebook and LinkedIn groups, aimed at undergraduate engineering students with a minimum of 1 year of CAD experience. Interested and qualified participants then completed an initial survey to collect demographic information. This study and its methodology were reviewed and approved by the University's research ethics board.

Of the 20 participants, 15 identified as men and five identified as women. The majority (12 out of 20) of participants were mechanical engineering undergraduate students. Other notable majors included engineering science (4 of 20) and chemical engineering (2 of 20). All participants were considered as "novices" that had a minimum of 1 year of parametric CAD experience; most participants (14 of 20) had 2–3 years of CAD experience, while 2 participants had less than 2 years, and 4 participants had more than 3 (but less than 4) years of experience. In terms of CAD packages, participants had the most prior experience using SOLIDWORKS (16 of 20) and FUSION360 (10 of 20).

4 Results and Discussion

4.1 Team Size and Productivity (RQ1 and RQ2). In this study, each team is evaluated on their *productivity score* in completing the assembly tasks. We define productivity score as the number of mates added by each team per modeling time. It should be noted that we only considered "correct mates" in our calculation of a team's productivity score. Mates were deemed correct if they produced the desired relative motion between the two components of the model. Errors were not counted as productive. We considered two different measures of time: calendar time (CT) and person-hours (PH). Calendar time serves as the actual elapsed time, equivalent to the amount of time a theoretical client would need to wait for the assembly to be completed, whereas person-hours is the total cumulative time required to complete the assembly, or the amount of time a company would pay in salary costs. Value added per calendar time is given in mates/minute, and value added per person-hours is given in mates/minute/person in the team.

Figures 5 and 6 show each team's productivity score (in calendar time and person-hours) for Round 1 assemblies and Round 2 assemblies, respectively. The figures also show each team size's average productivity score. The Quick Return, Schmidt Coupling, and Screw Jack models were assembled by the teams in Round 1, while the Cardan Joint and Manual Clamp models were assembled by teams in Round 2. It should be noted that due to our small sample size (two teams per team size), confidence bounds were purposely excluded, and thus no statistical claims are made.

When comparing teams based on calendar time, it can be seen that multi-user teams outperformed single users. The average productivity score in mates/min of 4-person teams was, on average, more than double that of single users.

In terms of person-hours, multi-user teams performed comparably to single users, and in many cases, performed slightly worse than single users. Our findings align with Penta et al.'s findings, which state that single users perform more efficiently than teams, because larger teams require extra communication overheads to coordinate and allocate tasks [62]. Thus, if a company is aiming to minimize labor costs, or if the completion deadline of a project is not urgent, it may be advantageous to hire a single user, instead of a team for CAD assembly.

It is notable, however, that across all five out of five assemblies, pairs tended to outperform single users in both calendar time and person-hours. This suggests the presence of an "assembly bonus effect" among pairs, where the team's contribution exceeds the combined efforts of each individual [63]. This outcome is contrary to previous studies in paired CAD collaboration research, which shows that on a per-person basis, individual designers complete CAD tasks faster than pairs, due to overheads for communication and coordination [58,64]. This could be attributed to the fact that paired designers in our study are modeling an assembly rather than a single part, which made task division and allocation more straight-forward, due to the lack of hierarchical feature dependency. Furthermore, the audio recordings indicated that teammates in 2-person teams were able to play to their strengths. Each individual was more inclined to add the mates they knew how to do first, became familiarized with their particular subassembly, and likely specialized in their respective tasks. Moreover, we know from the exit survey responses that many participants (7 of 20) expressed the benefits of having team members to ask questions. Participants stated that they found it helpful to have a second set of eyes to locate mistakes and a second person to troubleshoot with and bounce ideas off of. Therefore, our data suggest that participants were slightly more effective in a paired setting, than if they were alone. It is important to note that only pairs exhibited this bonus effect. We conjecture that larger teams experienced more communication overheads, which detracted from modeling time.

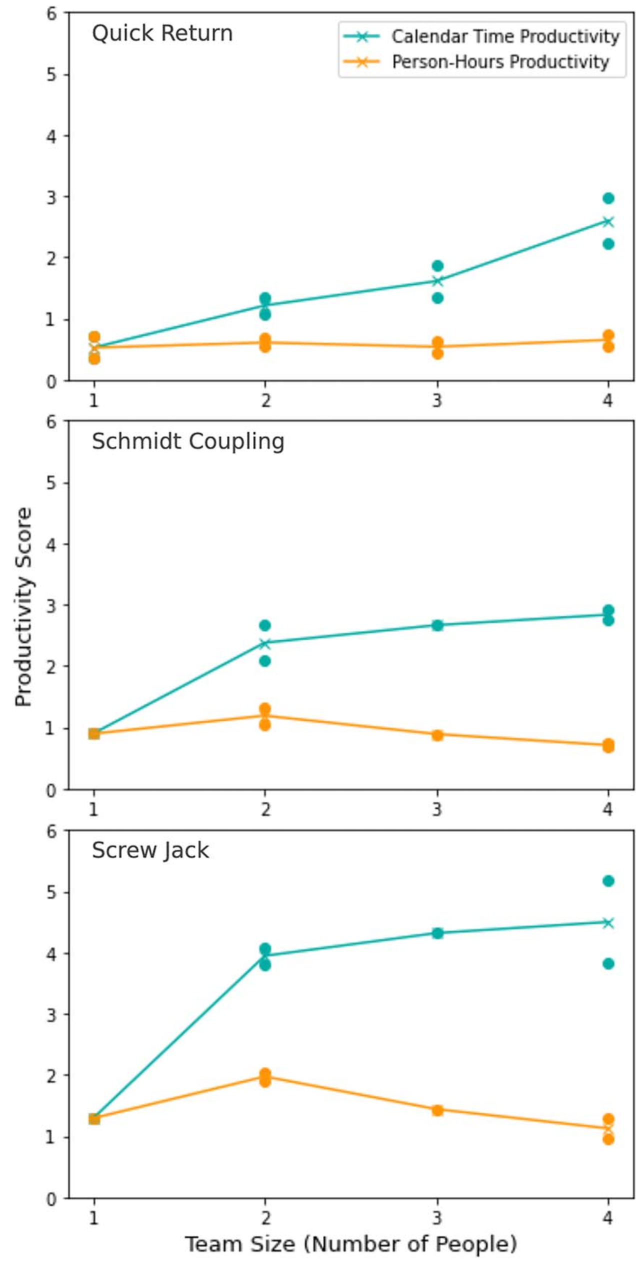


Fig. 5 Team productivity score of Round 1 assemblies from least complex assembly (top) to most complex assembly (bottom). Each circle represents the productivity score of one CAD team, and each *X* represents the average productivity score of each team size.

We expected that the more complex models would take longer to complete than the less complex models. However, the results suggest that the opposite is true. From the Round 1 assembly productivity scores, we observe that teams of every size become more productive as the assembly complexity increases. We conjecture that this effect may be attributed to learning, as participants began with assembling the lower complexity model (*Quick Return*), then proceeded to the medium complexity model (*Schmidt Coupling*), and finished with the most complex model (*Screw Jack*). A CAD learning study conducted by Hamade et al. found that students' CAD skills improved with (1) more time spent using the software, (2) increased familiarity with the UI, and (3) strategy/planning skills that come with more CAD experience [65]. In the study by Hamade et al., students improved faster at the start of the study, and proficiency leveled off as more time

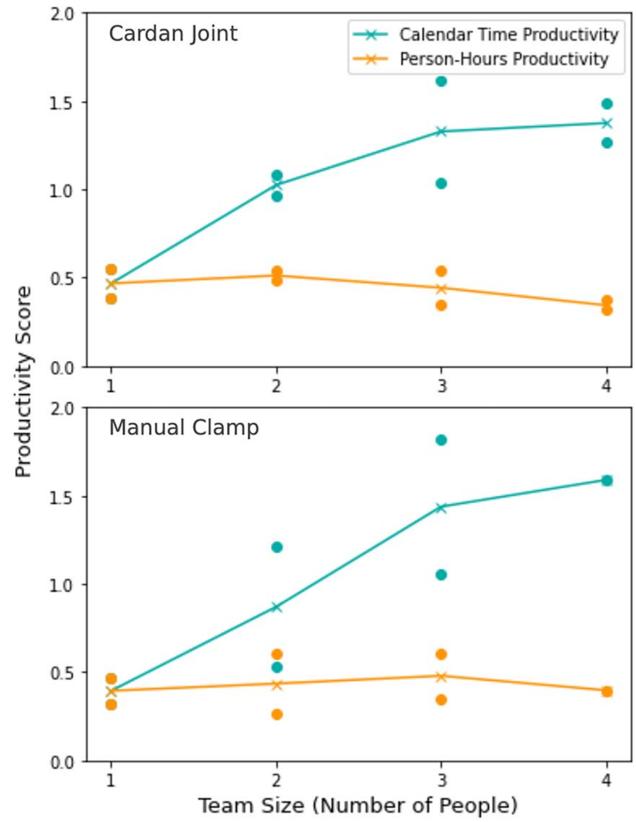


Fig. 6 Team productivity score of Round 2 assemblies from least complex assembly (top) to most complex assembly (bottom). Each circle represents the productivity score of one CAD team, and each *X* represents the average productivity score of each team size.

had elapsed. Therefore, participants in our study could have increased performance because as they assembled more models, they became better at selecting the appropriate mates, more familiar with the UI, and more comfortable working with their teammates, having already established a workflow plan. This learning effect may also play a role in why there is no significant change in team productivity in the Round 2 assemblies between the low and medium complexity model. It is possible that the CAD learning curve began to level off.

Overall, for all five assemblies, the increase in productivity across the four team sizes tended to follow the same general trend, which suggests that assembly productivity scales well with complexity. We presume this is the case because mates in assemblies are not hierarchically dependent. When modeling a complex part, a CAD team must place a great deal of emphasis on selecting a proper feature sequence. As a part becomes more complex, more intricate planning is needed, and the possibility for errors increases. In an assembly, however, the assembly order is less crucial. This means a team can focus their time on adding mates, rather than determining the "correct" assembly sequence. In fact, some teams reported that they preferred collaborating on the more complex assemblies because the increased number of mates resulted in fewer opportunities to overlap and disrupt each other's workflow.

Our study preliminarily indicates that teams can complete a CAD assembly in a shorter calendar time than single users. Successful teams allocated tasks that team members executed in parallel, thus helping to minimize the overall assembly time. While teams were faster in calendar time, our results suggest that in most cases, single users were more productive per person-hour than multi-user teams. The exception to this trend is with 2-person CAD teams, which contradicts prior work. Our data show that pairs consistently outperformed single users, across all assemblies.

4.1.1 Modularity. When given an assembly task, we anticipated that multi-user CAD teams would first analyze the full assembly, agree on a modularization of the assembly into subsystems, and then assign each subsystem to an individual or subset of individuals to assemble. By modularizing the assembly, team members are able to add mates in parallel, which could potentially reduce assembly time and increase productivity. In order to visualize these subassemblies, network diagrams are used to display the team's workflow.

In this section, we take a closer look at one particular assembly model: the Manual Clamp. We chose to describe and discuss this model in detail, because the workflow for each team size shows a very specific strategy. By analyzing these network diagrams, we may gain a deeper understanding of the factors that could influence the way a single designer or a team approaches an assembly task.

Figure 7 shows the modularity of the Manual Clamp assembly as established by a single user, 2-person, 3-person, and 4-person teams. Each node (i.e., solid circle) represents a mate added by a particular team member. Nodes that are connected with lines were created by one team member. The nodes are also numbered chronologically, to show assembly order and periods of overlapping work (e.g., the first mate added is denoted with "1," the second mate "2," etc.). Figure 7 additionally includes each team's productivity score, as measured by CT and PH.

As shown in Fig. 7(*a*), single users generally worked in a linear process because they were in complete control of their assembly elements. They did not encounter the issue of components being moved by their teammates. Since their workflow was uninterrupted

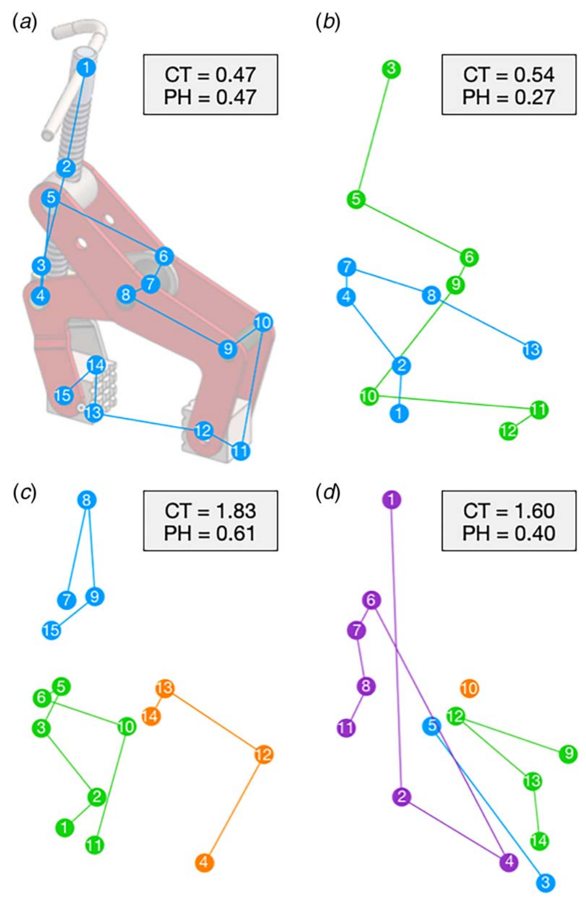


Fig. 7 Network diagrams of manual clamp assembly modularity of (*a*) single user, (*b*) 2-person team, (*c*) 3-person team, and (*d*) 4-person team. All nodes created by the same team member are the same color (e.g., blue, green, orange, and purple) and connected with straight lines. The productivity scores for each team are provided in the shaded gray rectangle, in both CT and PH.

by other contributors' actions, single users could begin assembling at one end of the assembly and follow the geometry of the model. This single designer had a productivity score of 0.47 mates/min.

We anticipated that low-performing teams would have different plannings and methodologies than high-performing teams. The most common modularization style used by nearly all teams was to spatially decompose the assembly by "zone." In this zonal approach, participants selected sections of the model and created all mates that fell within their respective sections. Teams that followed this approach commonly said phrases such as, *"I'll start from the top, you start from the bottom"* or *"I'll start from the left, you start from the right."* Teams that chose effective modules worked in their agreed-upon zones and had no overlap. The 3-person team in Fig. 7(*c*) displays this work arrangement where the geometry was divided into upper, lower left, and lower right modules. On the other hand, the 2-person team in Fig. 7(*b*) had an overlapping workflow. From the audio recording, we learned that this team attempted to modularize (with upper and lower modules) but did not choose the most effective subassembly structure, which led to reduced productivity and a low productivity score. As shown in Fig. 7, the 2-person team achieved a productivity score of 0.54 mates/min, while the 3-person team achieved a productivity score of 1.83 mates/min. Even though both the 2-person and 3-person teams completed more correct mates than the single designer, the 2-person team had a lower person-hour productivity score (0.27 mates/min/person). In contrast, the 3-person team surpassed both the single designer and the 2-person team, achieving a person-hour productivity of 0.61 mates/min/person. While we cannot attribute this higher productivity to either modularization or task division strategies, this observation does point toward a potential relationship that warrants further exploration.

The 4-person team modularized relatively effectively, with minimal workflow overlap. From Fig. 7(*d*), it is evident that the purple user added significantly more mates than other team members. This participant was slightly more experienced in CAD than the other three, and likely contributed beyond their assigned module to assist the rest of the team. Therefore, it is possible that this team could have avoided overlapping subassemblies if individual contributions and CAD skill levels were more balanced. This imbalance could also relate to the team's lower person-hour productivity score, of 0.40 mates/min/person, compared to the efficient 3-person team and single designer.

4.2 Communication and Team Productivity (RQ3).

Effective communication is crucial to the success of an engineering design team [66,67]. We define effective communication as communication that aids in team productivity, such as sharing progress, building a shared mental model, allocating tasks, and answering questions. Ineffective communication, such as off-topic discussions, can distract from the task at hand, thus harmful to a team's productivity. In previous work by Stone et al., it has been shown that successful CAD modeling teams have a large initial spike in communication for planning, followed by minimal communication throughout the majority of the task, and a smaller communication spike at the end to summarize what was done. Alternately, the least successful teams communicate consistently throughout the task due to poor planning [51].

In order to identify and analyze communication patterns across different teams, we generated waveform graphs from the audio recordings of each team for each assembly. Figure 8 shows the communication pattern of the best- and worst-performing team from the Screw Jack assembly task. It should be noted that in this particular assembly, both the best-and worst-performing teams were two-person teams. Some may contend that it is easier to minimize communication in a two-person team, compared with a larger team with more people to coordinate. However, we find similar trends even amongst larger, four-person teams. Figure 9 shows the communication pattern of the best-performing 4-person team and the worst-

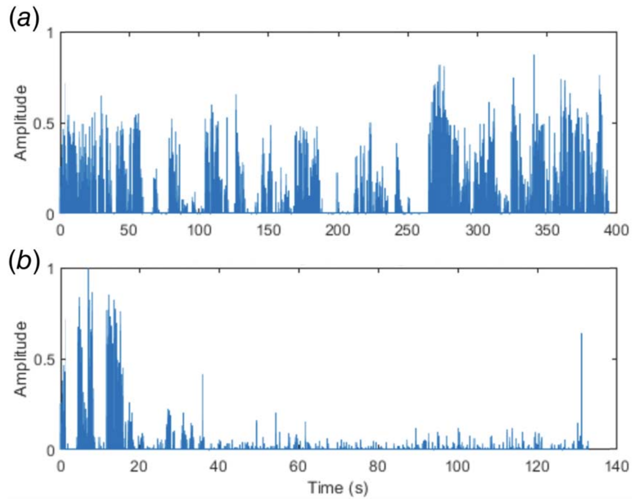


Fig. 8 (*a*) Worst and (*b*) best performing team for the Screw Jack assembly

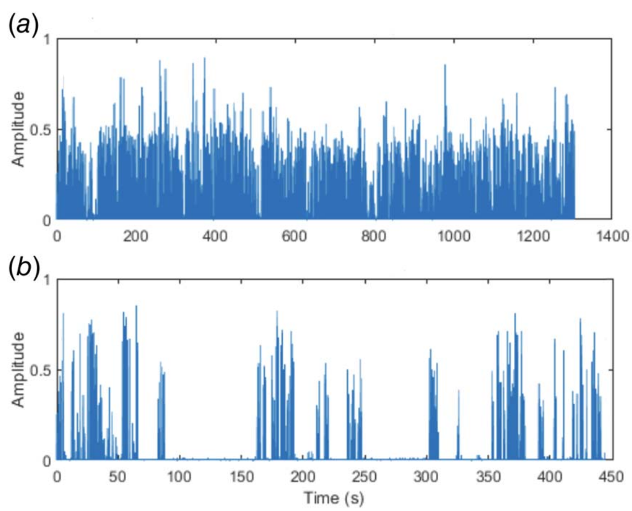


Fig. 9 (*a*) Worst and (*b*) best performing 4-person team for the Cardan Joint assembly

performing 4-person team from the Cardan Joint assembly. Although the best-performing team displayed more communication spikes than anticipated, they followed the same general trend of an initial communication spike followed by substantial periods of silence.

To provide additional context to the communication topics, we listened to the audio recordings. We found that high-performing teams initially communicated to plan assembly order and allocate work, likely resulting in a strong shared mental model. With productive planning, team members felt confident to complete their assigned tasks with minimal direction and input from the rest of the team. In contrast, low-performing teams communicated nearly constantly, perhaps because team members did not have a sufficient shared mental model. Since members in the low-performing teams were unsure of what to do, these teams continued to discuss how the parts should move and which mates were correct throughout the assembly task. As a result, low-performing teams were not able to allocate and execute tasks like high-performing teams did.

Overall, we observe a distinct relationship between communication frequency and team performance. Our evidence supports that the worst teams communicated more frequently than the best teams. The most productive teams communicated effectively, with a large initial spike in conversation for planning, then minimal communication throughout the task, periodically checking in to give progress updates and ask questions, if needed. Teams that displayed constant communication failed to build a shared mental model and struggled to complete tasks independently. In this case, communication and coordination overheads may have negatively impacted a team's productivity. It is also important to note that the most and least successful team in each of the five assemblies were not always of the same size. In other words, no particular team size exhibited consistently poor or superior behavior. Every team has the potential to communicate effectively or poorly, regardless of its size.

4.3 Collaboration Challenges and Recommendations (RQ4). We qualitatively open-coded the post-experiment survey responses and the audio transcriptions from the synchronous assembly tasks, to identify common challenges experienced by the multi-user CAD teams as well as recommendations on how to mitigate these challenges. In the following paragraphs, we present the most common challenges and recommendations mentioned by the study participants. The first two challenges and associated recommendations are related to how collaborative CAD platforms can improve their features, functionality, and user interface. The last two challenges and recommendations are relevant to how multi-user CAD teams should plan, organize, and execute their work.

Challenge 1: Insufficient awareness of teammates' actions

As expressed by 13 participants, it was difficult to effectively communicate to and interpret from teammates which parts the teammates were mating. The lack of clarity caused teams to communicate back and forth excessively, which took time away from assembling, as one participant explains:

> *"It was unclear sometimes which parts the team member was working on, because the interface didn't show the member's activities in detail. The interface would only update when the part design was completed. We could not see who was working on which mates, which parts people were selecting and the real-time updates of the part mates."*

While ONSHAPE does have a "Follow Mode" feature which allows users to view another collaborator's screen in real-time, this proved to be insufficient:

> *"Explaining your view relative to the other user was difficult. It was possible to view their [point of view] which helped with collaboration, but was still somewhat cumbersome."*

Recommendation 1: New software features to enhance designers' awareness of collaborators' actions

In order to improve synchronous collaboration in CAD assembly, we propose three features: (1) ability to view other users' cursor location, (2) highlighting the part that other users have selected, and (3) color-coding mates in the feature tree. Throughout the assembly tasks, participants frequently asked their teammates to what degree they could view each other's activities. Giving users the ability to see their team members' cursors will make it easier to explain each user's relative position in the assembly, as well as pinpoint which person is working on each part. Similarly, it is recommended to enable all collaborators to be able to view the highlighted part that each teammate has selected. This feature is similar to that of Google Docs, where all collaborators can see the text that is selected by their teammates, in each collaborator's unique color and cursor. Finally, mates in the feature tree should be tagged with each collaborator's unique color and first initial. This will assist collaborators in quickly seeing who was responsible for each mate.

Challenge 2: Component relocation interrupts workflow

As mentioned in 8 of the participant exit surveys, during team assembly, parts that one user would be working on would frequently be moved out of view by a teammate, which disrupted the user's workflow. Participants reflected that the actions of their teammates would negatively impact their productivity:

"It was somewhat distracting having multiple people within a given assembly as for example I would be trying to make a mate and the part that I had intended to select would sometime be moved out of view because of something my teammate had done within the assembly leading to some lost time and a little bit of confusion/frustration."

Recommendation 2: Change transparency of first selected part

We propose for collaborative CAD platforms to enable a transparency function, such that when adding a mate, the first selected part becomes transparent. This way, the frequency at which parts must be moved is reduced, resulting in less disturbance to other teammates who can continue to do their tasks. One participant expresses that this transparency function, which is present in traditional CAD, would be helpful if implemented in collaborative CAD.

"One thing I don't like about this is like, you know, in SOLIDWORKS, when you click for mating, like it'll make the one part you just clicked go transparent. I feel like with [ONSHAPE], you got to move the parts out of the way. I also don't like how it doesn't immediately —like if you haven't clicked on a part already and then click the mate—it doesn't already include that part."

Challenge 3: Ambiguity with duplicate components

In the less complex models (i.e., Quick Return and Cardan Joint), all teams relied on the unique part colors and names to identify and differentiate parts. Some of the more complex models (i.e., Schmidt Coupling and Screw Jack) had multiple copies of parts within the assembly. For example, the Screw Jack assembly comprised eight copies of a yellow connecting bar. The lack of a unique identifier for each part made it difficult for team members to describe their activity and to allocate tasks. Of the total 20 participants, 9 mentioned this challenge.

"The Screw Jack had multiple linkages that looked exactly the same which made communicating which part I am working on harder."

Recommendation 3: Assign each part a unique identifier

One way to reduce the ambiguity that comes with having identical parts in an assembly is to ensure each part in the assembly is unique. This can be done using different colors or renaming parts in the assembly in the feature tree. By giving each part a unique identifier, teams will have an easier and faster time describing a specific component.

Challenge 4: Overlapping and duplicate work

If tasks were not clearly or properly delegated, a common challenge that arises is the insertion of duplicate mates between the same two components by multiple team members, resulting in overlapping work and an over-constrained assembly. In addition to causing annoyance and frustration in some groups, such overlapping work is also inefficient since team members must spend time reviewing the feature tree to revise previous mates. This challenge was reported by 12 participants. The comment below illustrates:

"It was difficult to see what the other members were doing or what items they were clicking. We had multiple people placing repetitive mates and our system kept producing errors. One other member and I had to keep deleting overlapping mates and try to troubleshoot as the other members kept making mates."

Furthermore, the virtual setting made it difficult to pick up on non-verbal cues from each teammate. In an in-person scenario assembling physical objects, it is obvious which person is handling a particular object, making it easy to avoid inadvertently grabbing the same object. In collaborative CAD, however, it was common for teammates to select the same part; 6 participants mentioned this challenge. The following quote from a participant to their teammates during the experiment depicts a scenario where each teammate is trying to mate the same two components, because it is unclear which teammate has the component in possession.

"Okay. One person do [the revolute mate] because I think I keep clicking a part at the same time that someone else is doing it."

Recommendation 4: Modularize and create subassemblies

To reduce overlap, it is recommended that teams modularize their assemblies into simpler, more manageable subassemblies. By doing so, team members can be focused on the mates within their respective section and avoid doing duplicate work. One participant motivates this recommendation below:

"It would have been nice to have subassemblies for each person on the team to work on before combining into an assembly. That would have greatly reduced the overlap and duplicate items in our group model."

4.4 Summary of Findings. Overall, we identified several factors that can affect the performance of a multi-user CAD team. One of the most important takeaways from our results is that regardless of team size, assembly complexity, and project urgency, taking time to strategize a plan is crucial to a team's efficiency. A successful action plan can help a team reduce redundancies and avoid duplicate and overlapping work. During the initial discussion, teams should analyze the assembly in sufficient detail such that each team member is adequately prepared to complete their assigned tasks with minimal direction. It is also valuable for teams to modularize their assemblies as a way to delegate work.

5 Limitations and Future Work

5.1 Limitations. Our study had a limited sample size of 8 teams, comprising 20 total participants. As such, we did not make statistical claims, and our results may overestimate the magnitude of the relationship between productivity and team size [68].

We recruited undergraduate engineering students, not professional CAD designers. Although participants were required to have 1 year of prior CAD experience, only a small subset of our participants (10%) had previous ONSHAPE experience. Realistically, a 25-minute guided training session is insufficient to fully master any CAD software, even with prior related CAD knowledge. Likewise, very few of the novice designers in our study had previously collaborated synchronously in a CAD system. It may be in the interest of future studies to investigate models assembled by expert CAD users. Furthermore, although similar work often recruits student participants [7,58,65,69], this limits our findings' generalizability to industry design practices. We acknowledge that assemblies created by professional design teams could be far more complex than those presented in our study.

5.2 Future Work. This research is among the first to investigate assemblies in collaborative CAD. As such, we identify many areas that can be explored in future work.

A natural progression of this work is to explore a wider range of CAD proficiency levels and recruit professional CAD designers to participate in our study. Analyzing expert designers working with more complex assemblies would not only improve the generalizability of our findings, but also help us validate whether CAD assembly work truly scales well with complexity.

Future work will also consider additional metrics for measuring the performance of a team, beyond productivity, such as the quality of the assembly, frequency and magnitude of team conflicts, more collaboration instances, and designer emotions and satisfaction, as has been done in similar collaborative part modeling literature [58,64,70].

Finally, we are interested in investigating the effect of other mediums of virtual communication (e.g., video conferencing) on the design process. In our work, participants were instructed not to turn on their video and could not see their collaborators' faces throughout the synchronous design process. The use of video conferencing in virtual collaboration can more closely mimic in-person collaboration—which has been suggested to result in greater design exploration and variety [71]—by enabling non-verbal cues, facial expressions, and gestures that can enhance communication and foster a stronger sense of social presence among team members.

6 Conclusion

Our research investigated virtual student teams collaborating on CAD assemblies of varying complexity. We analyzed audio recordings, team activity, and survey responses to understand how designers can employ collaborative CAD for the assembly phase of CAD design work.

Our results support that multi-user teams can complete an assembly in less calendar time than a single user, across all levels of assembly complexity. We recognize several differences in the behavior of successful teams versus unsuccessful teams. The best-performing CAD teams planned efficiently, modularized assemblies into separate and more manageable subassemblies, executed tasks in parallel, and communicated minimally, but effectively. It was found that communication and coordination overheads detract from assembly time, making teams less efficient than single users in person-hours. However, an assembly bonus effect is present among paired collaborators, because each teammate can specialize in their individual strengths. Teammates in multi-user teams could also offer each other ideas and assistance during periods of struggle.

These findings highlight notable implications for design teams and collaborative CAD platforms. By comparing successful and unsuccessful teams, we identify factors that affect the productivity of teams working in collaborative CAD, as well as provide suggestions on how to increase efficiency in future team assemblies. Our research can help design teams improve assembly workflow, task allocation, and communication. Finally, we propose new features that collaborative CAD platforms can implement to facilitate designer collaboration in CAD assemblies. Our work supports the claim that collaborative assembly activities have the potential to improve the capabilities of modern product design teams, to ultimately deliver products faster and at lower cost.

Acknowledgment

Thank you to the students who participated in our study. Without you, this work could not be possible.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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